Neural-Net Application-Study on CAD System for Magnetic Macro- to Micro-Machines

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As positive neural-net applications we consider how to construct a CAD (computer aided design) system for magnetic machines of macro to micro sizes. According to order's requirements, computers choose one of appropriate materials and determine the best shape of magnetic machines. Finally the best material is also determined in the computation process. Shapes of magnetic machines in various sizes are derived and their characteristic features are discussed. Furthermore, we discuss the most preferred numerical grid system (chosen according to the variational principle) and fundamental treatments of the Maxwell equations for the nanomachine-design.

1. Introduction

By the positive use of the concept of the neural net, studies on intelligent, materials, machines and processing in addition to intelligent control are eagerly desired to create new, important science and technology from the usual size to the nano size through the microsize. Fundamental subjects there consist of how to produce intelligent materials, to design intelligent machines and to process them intelligently, with the aid of newly developed brain computers. In particular, towards the nano science and technology we think of the necessity of the following developments: (1) Generally, characteristic properties of intelligent materials in such fields appear from low dimensional properties such as quantum dots, strings or interfaces, rather than three dimensional bulk properties, i.e. combination of elements and topological structures folded with them as a bulk play an important role in the development of intelligent materials, utilizing the first, the second or higher order phase transitional properties [e.g. in intelligent nano materials of magnetism (including opto-, piezo-, thermo-, elasto- and superconducto-magnetisms), superconductor and liquid crystalline polymer, in addtion to the corresponding materials of semiconductor and electrics (including piezo- and thermo-electrics)]. (2)Intelligent machines with integrated thinking parts like a brain computer should be designed and processed with the aid of computer. They are effectively self-controllable and work for given purposes with small amount of energy. (3)Intelligent processing for the most appropriate materials and machines is performed through the processes of in situ structure-measurement, in situ structure-analysis and in situ structure-control from the phase transitional point of view. (4)For intelligent control in the processing and machine-movements we need further study of brain computers with human-like functions.

For such purposes, using our modified neural-net algorithms, we are studying fundamental problems of neural networks [1], the CAD systems of macrosized magnetic machines [2,3] and fundamental processing problems of in situ structure-analysis [due to X-ray photoelectron scattering] and in situ structure-control of semiconductor materials [4], in addition to experimental studies of nano superconducting materials.

In section 2 we consider how to design macro- to microsized magnetic machines. Firstly, we consider fundamental equations required for it and leading principles of design in 2.1 and 2.2, respectively. Secondly, we consider the design of superconducting and permanent magnetic machines in 2.3 and 2.4, respectively, and their characteristic features obtained are also discussed there.

In section 3, to improve our CAD System, we discuss the most preferred numerical grid system chosen according to the variational principle. Towards nanomagnetic machines we discuss how to formulate fundamental equations for electromagnetic phenomena in section 4. As nanomaterials are regarded as disordered media they are derived and discussed, using the supersymmetry field. Finally, in section 5 concluding remarks are summarized.

2. Micromagnetic Machines

Magnetic machines have the following advantages: Macrosized machines excel in generation of homogeneous fields, while microsized machines have a tendency to generate relatively inhomogeneous fields. Here for simplicity we consider CAD systems of simple machines in the shape of an uniaxial symmetry, which yield the magnetic field with required strength and uniformity. Those of cases in which we make use of particular inhomogeneous fields will be discussed in the near future.

2.1 Fundamental Equations

For the design of the macro- to micro-sized magnetic machines Maxwell equations can be used under the material relations of the conduction-current density distribution $\mathbf{j}_c$ and/or the magnetic flux density $\vec{B}$- magnetization $\vec{M}$ distribution (which reduces to the magnetization current density $\vec{j}_M$ = rot $\vec{M}$). By the total circular current J with radius a, the magnetic flux density is generated as

$$\begin{aligned} B_r(r,z) &= (-\mu Jz/2\pi C_1)[E(k)C_3/C_2 - K(k)], \\ B_z(r,z) &= (\mu J/2\pi C_1)[E(k)C_4/C_2 - K(k)], \\ B_\phi(r,z) &= 0 \end{aligned} \tag{1}$$

with $k^2 \equiv 4ra/C_1^2$, $C_1 \equiv [z^2 + (r+a)^2]^{\frac{1}{2}}$, $C_2 \equiv (r-a)^2 + z^2$, $C_3 \equiv r^2 + a^2 + z^2$, $C_4 \equiv r^2 - a^2 + z^2$, where K(E) stands for the first (second) kind of the complete elliptic integral. The current J is taken into account over the whole conduction and/or magnetization current. The magnetization current distribution is self-consistently determined through the B-M curves.

Fundamental equations for the design of the nanosized machines will be discussed later.

2.2 Leading Principles of Design

Characteristic data {properties, price} of superconducting coils and magnetic materials are listed in a database [MD]. Order's requirements {field strength, uniformity, working area, etc.} are also in a database [RD].

Machines are assumed to consist of a single [solenoidal type] or double pieces [Helmholtz type] with a gap length $g(\equiv 2g_z)$, which shape a cylindrical [radius g_r] or ellipsoidal [radii a_r, a_z] inner-surface and the shape of whose outer-surface is determined so as to minimize the cost, i.e. the coil length and/or the material volume used.

To raise the efficiency of recursive computation for the determination of magnetization distribution and/or the outer-surface, our improved Boltzmann machines [2,3] are used.

The final goal is to design the magnet of the best material with the most suitable shape for the order's requirements.

Brief explanation of the method of design is as follows: Under an initial outer-surface shape assumed we divide the magnetic media into cells and assume a set of initial magnetization distribution. Summing over whole contributions of the total currents in each cell to the magnetic flux density we get a new set of magnetization distribution through the B-M curves. Replacing a set of initial magnetization distribution with a suitable distribution expected by the learning algorithm, we get a set of self-consistent magnetization distribution and the magnetic field distribution in space from this distribution. Using the learning algorithm, the most preferred outer-surface shape is computed, to minimize the cost used. Finally the best material is determined to minimize the total cost.

The improved learning algorithm is useful for the self-consistent determination of the magnetization distribution and the outer-surface shape, regarding a set of the k -th (k+1-*st*) data as the association (recalling) layer.

2.3 Design of Superconducting Magnetic Machines

Similar to the macrosized superconducting magnetic machines like the magnetic resonance image [MRI] and the nuclear magnetic resonance [NMR] [2], the design of the microsized superconducting magnetic machines [to generate uniform fields] can be made and has the following features.

Using the MD-database the most preferred magnetic shape of the best material is determined, whose magnet satisfies the order's requirements. Then, the type [cylinder or ellipsoid] and size of its inner-surface are treated as a changeable parameter.

Let us summarize the characteristic features or various types of designed machines.

A.Cylindrical Inner-surface

A.1 Traditional Helmholtz type; **1**. the production is easy, **2**. the uniformity of the magnetic field is limited in a narrow region, and **3**. long winding-wire length is required.

A.2 Modified Helmholtz type; **1**. the shape of the outer surface is not simple but its production is easy, **2**. the uniform magnetic field is produced over wide regions, **3**. the compensating coil part is naturally added, and **4**. the winding-wire length is reduced by about 20-30%.

B.Ellipsoidal Inner-surface

B.1 Solenoidal type; **1**. the magnetic field is uniform over wide regions, **2**. the winding-wire length is further reduced by 40-60%, and **3**. there are universal shapes independent of the field strength i.e. they are almost near the ellipsoidal as the ideal limit.

B.2 Helmholtz type; **1**. the magnetic field is uniform over wide regions, **2**. the winding-wire length is further reduced than that of A.2, **3**. the compensating coil part is naturally added, and **4**. there are universal shapes independent of the field strength, as in the sense above.

2.4 Design of Permanent Magnetic Machines

As well as the macrosized permanent magnetic machines [3], we can design microsized permanent magnetic machines. The differences from the former section are as follows. The cell magnetization is assumed to be uniformly distributed with the magnetization at the center of the corresponding cell, i.e. the magnetization current reduces to only the surface current. The computing process is added to determine a self-consistent magnetization distribution. Thus the CAD system is constructed from four steps; database on information of magnetic materials, selection of the best material, decision of the best outer-surface shape of magnets, and computation of the self-consistent magnetic distributions.

Machines are assumed to consist of a single [cylinder type] or double pieces [Helmholtz type] with a gap length g, whose inner-surface shape is cylindrical with radius g_r or ellipsoidal with radii a_r, a_z and whose outer-surface shape is determined so as to minimize the cost.

As a result of computation, the case of spherical or ellipsoidal inner-surface is most appropriate to generate uniform fields over wide regions, whose outer-surface is relatively simple, cylindrical- or ellipsoidal-like.

The characteristic features of the permanent magnetic machines CAD using neurocomputing are summarized as follows. (1) The computing time is drastically shortened. (2) The computing accuracy considerably increases. (3) The solutions are found in terms of appropriate annealing procedure. (4) Our method is applicable to any magnetic material. (5) Our method is applicable to macro- to micro-sized machines.

3. The Most Preferred Numerical Grid System

To improve our CAD system based on the neural-net algorithm we consider the most preferred numerical grid system, automatically chosen according to the variational principle.

In the method described above, magnetic media are divided into subspaces whose cell-size is chosen to be same in the identical subspace but different in different subspaces. This fixed grid system has the following features; (1) it maintains the highest speed in computation since we memorize and avoid repeatedly to compute identical values relating to (intracell-) distances and the complete elliptic integrals, (2) it also gives rough values in regions of rapidly changing fields, and furthermore, (3) it approximates boundaries of magnetic media with surfaces of fixed cells.

The most preferred numerical grid system is constructed as follows. The number of grids is unaltered. The numerical grid is chosen to fit the grid surface for boundaries of the magnetic media. Inside the magnetic media it is chosen so that the magnetic field distribution may be computed with sufficient accuracy. As this distribution evolves with time, the structure of numerical grid also evolves so that the grids may concentrate into the regions with large gradient. The integral to be minimized $[I \equiv \int F[g, w(x)]d\xi]$ is supposed to be a function of a metric tensor g and a weight $w(x)$ depending on positions x in the physical space. New numerical grids are generated by a set of Euler equations [5]. The problems here and how to solve them are as follows. (1) As long computing times are required for derivation of the final, accurate magnetic distribution, we adopt the method in which after we compute a self-consistent magnetization distribution under some fixed numerical grids we change them into more suitable numerical grids and repeat the same recursive computation until the most accurate distribution is derived. Here the high speed techniques described above can be utilized. (2) What is the simplest and the best way to determine the numerical grids? Numerical experiments are going forward. (3) Using neural network algorithms together with the generation of the numerical grids we try to find a new approach.

4. Towards Nanomagnetic Machines

Towards nano machines we consider how to formulate electromagnetic fields. Nano materials are considered to be in disordered media. These should be treated by both the methods of replica trick and supersymmetry [SUSY] field. Let us briefly describe the results obtained, avoiding theoretical details in the process of the derivation. According to the phenomenological Maxwell equations, the randomness of the media is expressed by the statistics of the random complex [permittivity $\varepsilon(\vec{r})$ and permeability $\mu(\vec{r})$] fields:

$$\begin{pmatrix} \vec{j}_s \\ \vec{m}_s \end{pmatrix} = \begin{pmatrix} i\omega\varepsilon & \text{rot} \\ -\text{rot} & i\omega\mu \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} \qquad (2)$$

where $\vec{j}_e(\vec{m}_s)$ is a source for the electric (magnetic) current. Using complex test sources $\vec{j}_t$, $\vec{m}_t$ the characteristic functional is specified as

$$F(\vec{j}_t, \vec{m}_t) \equiv ln\langle \exp i2\ Im \int d\vec{r}[\vec{j}_t^* \cdot \vec{E} + \vec{m}_t^* \cdot \vec{H}]\rangle, \qquad (3)$$

from which all correlation functions of the fields $[\vec{E}, \vec{H}, \vec{B}, \vec{D}]$ are derived as the average values.

Introducing the SUSY field to take the random-average, we get the conclusion that only contributions to F consist of terms expressed with diagrams without closed loops. The expectation values of $\vec{E}$ and $\vec{H}$ [drawn with a single solid line] are derived as

$$\begin{pmatrix} \langle\vec{E}(\vec{r})\rangle \\ \langle\vec{H}(\vec{r})\rangle \end{pmatrix} = \int d\vec{r}' G(\vec{r}, \vec{r}') \begin{pmatrix} \vec{j}_s(\vec{r}') \\ \vec{m}_s(\vec{r}') \end{pmatrix} \qquad (4)$$

with

$$G = \langle \begin{pmatrix} i\omega\varepsilon(\vec{r}) & \text{rot} \\ -\text{rot} & i\omega\mu(\vec{r}) \end{pmatrix}^{-1} \rangle \quad (5)$$

where the mass operator Σ is defined as

$$\text{G}^{-1} = \text{G}_0^{-1} + iw\ \Sigma. \quad (6)$$

The matrix $T \in \{G, \text{G}_0, \Sigma\}$ is constructed with 4 blocks of T_{ij} $(i, j = \text{E}, \text{H})$, each of which is a 3×3 tensor for given $\vec{r}, \vec{r}'$. We assume that the media are macroscopically not only homogeneous but also isotropic. We can get

$$\text{G}^{-1} = \begin{pmatrix} iw(AP_1 + BP_2) & iC\vec{k}\times \\ -iC\vec{k}\times & iw(A_m P_1 + B_m P_2) \end{pmatrix}$$

where A, B, A_m, B_m and C are complex functions of k^2 and ω, and $P_1(P_2)$ stands for the transverse (longitudinal) projection matrix. Then, the effective permittivity and permeability are related as

$$\begin{aligned} \langle\vec{\mathbf{D}}\rangle &= [\{A - C(C-1)k^2/\omega^2 A_m\}\ P_1 + BP_2]\ \langle\vec{\mathbf{E}}\rangle, \\ \langle\vec{\mathbf{B}}\rangle &= [A_m/C]P_1\ \langle\vec{\mathbf{H}}\rangle \end{aligned} \quad (7)$$

which are also expressed with the sources

$$\begin{pmatrix} \langle\vec{\mathbf{D}}\rangle \\ \langle\vec{\mathbf{B}}\rangle \end{pmatrix} = \begin{pmatrix} (a_1a_2 + a_3) & -a_1\vec{\mathbf{a}}_4 \\ a_1\vec{\mathbf{a}}_5 & (a_1a_2 + a_3) \end{pmatrix} \begin{pmatrix} \vec{\mathbf{j}}_s \\ \vec{\mathbf{m}}_s \end{pmatrix} \quad (8)$$

using $a_1 \equiv i/(C^2k^2 - \omega^2\ AA_m)$, $a_2 \equiv (C/\omega)k^2P_1$, $a_3 \equiv 1/(i\omega)$, $\vec{\mathbf{a}}_4 \equiv Ak\times$ and $\vec{\mathbf{a}}_5 \equiv A_m k\times$. The lowest order contribution to the mass term $\sum(\vec{k})[\equiv i\omega^{-1}(G_1^{-1} - G_0^{-1})]$ is expressed as

$$\Sigma_c(\vec{k}) = -i\omega \int d\vec{\mathbf{q}} \begin{pmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{pmatrix}$$

with

$$d_{ij} \equiv a_{ij}(\vec{k} - \vec{q})\langle\vec{b}_{ij}(\vec{q}, -\vec{q})\rangle_c \quad (9)$$

where $a_{ij} \equiv G_{1ij}$ $(i, j = E, H)$ and $b_{ij}(\vec{\mathbf{q}}, -\vec{\mathbf{q}}) \equiv i(\vec{\mathbf{q}})j(-\vec{\mathbf{q}})(i, j = \varepsilon, \mu)$. Here renormalization condition is imposed so as to satisfy $\Sigma = 0$ for $k = 0, k_R, \infty$ at $\omega = 0$ [i.e. $G(\vec{k}) = G_1(\vec{k})$] and the same residue of G as that of G_1 at $\vec{k} = \vec{k}_R$(pole).

To make this renormalization procedure effective, the following modifications are required. (1) To find small effective-expansion parameters, we replace the inductions $\vec{D}$ and $\vec{B}$ by $\alpha^{-1}[\vec{\mathbf{D}} + \beta\vec{\mathbf{E}}]$ and $\gamma^{-1}[\mathbf{B} + \delta\mathbf{H}]$, respectively, using small parameters $\alpha^{-1}, \beta, \gamma^{-1}$ and δ. (2) Developing the similar method described above and imposing the renormalization condition, we can get the final results corresponding to the order of the expansion. (3) According to the cluster size of materials, the degree of the randomness of ε, μ, and the order of the expansion are adjusted.

5. Concluding Remarks

Fundamental problems on design of macro-to micromagnetic machines have already solved here using the neural-net concept. Fundamental studies also have advanced in the fields of the in situ measurement, the in situ analysis and the in situ control of the material structures, in addition to the studies for the brain computer integrated in the machines. Problems of how to design their machines with complicated, intelligent functions will be accomplished in the near future.

Towards nanomagnetic machines various fundamental research has been performed and the time will come to be able to compare results obtained theoretically and experimentally.

Finally the intelligent control of the neural nets has advanced [6] and the neural nets will approach toward human-like functions, brain.

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